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THE STRUCTURAL FEATURES OF THE PLANETARY NEBULAE

by

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Introduction

Among celestial objects the gaseous nebulae present what has appeared to be the simplest and most easily understood of emission spectra. Accordingly, much attention has been devoted to the interpretation of these objects, particularly to the class of gaseous nebulae known as planetary nebulae. Not only have the spectra been studied in great detail, but extensive theoretical work has been done on the detailed mechanisms responsible for the excitation of the nebular emission lines, both the forbidden and the permitted lines. These theoretical investigations have proven fruitful, not only for the interpretation of nebular spectra, but also for the interpretation of the auroral spectrum and even the spectrum of the corona.

In making detailed applications of the theory to specific gaseous nebulae, it immediately became obvious that the observations then available were not adequate for the task at hand. The theory gives the rate of emission of energy per unit volume in specified spectral lines, e.g., $H\alpha$ or $\lambda 5007$ [OIII] in terms of the local electron temperature and density and of the abundance of the atom or ion in question. The observations give the relative intensities of the nebular lines, and in some instances the brightness of one of them, e.g., $\lambda 5007$, in terms of the flux received per cm^2/sec at the top of the earth's atmosphere. In order to reduce the observations to a form in which they can be compared with theoretical predictions we must have some information on the distance of the nebula and on its structure.

The distances of diffuse galactic nebulae can be found from the magnitudes and spectral classes of their illuminating stars. The distancesof the planetary nebulae with which we are concerned in this report are less easy to establish. Statistical methods based on the association of these objects with the central bulge of the galaxy and with globular clusters must be employed. Although substantial progress has been made, we are not yet in possession of accurate distances for the relatively nearby nebulae concerned in our present study. We have to use "statistical distances" such as those given by Berman. His scale of distances appears to be correct even though the value published for any particular object may be appreciably in error.

The spatial structure of the nebula presents, to some degree, an even more difficult problem. Some progress may be made if we can combine measures of the distribution of brightness over the nebular image with radial velocity data such as those obtained by Olin Wilson. Since the nebular shell is expanding, the displacements and relative intensities of the two components of the split spectral line combined with measures of the surface brightness at the point on the nebula where the velocity is measured, may suffice to permit an estimation of the three dimensional structure.

The present program is concerned with the determination of the surface brightness distribution over the face of the nebula by measuring the isophotic contours. Since the nebular radiation is concentrated principally in a few monochromatic lines and since different lines show different surface intensity distributions, studies of an ordinary photograph would be of little help. It is necessary to measure isophotic contours of the various monochromatic images of the nebula. Such images may be obtained with a slitless spectrograph or (very nearly) with appropriate filter and plate combinations.

2. Summary of Earlier Work

Louis Berman, at the Lick Observatory, measured the first isophotic contours of planetary nebulae on plates obtained with the quartz slitless spectrograph on the Crossley Reflector. He constructed these contours by the laborious process of making successive tracings across the monochromatic images and joining together on a two-dimensional map points corresponding to the same intensity. Later, the writer used the same method to get contours for the $\lambda 4686$ He II image in NGC 7662 and for the $\lambda 3727$ [OII] image in NGC 6720.

The disadvantage of the Berman method is that not only are the reductions extremely tedious but that there is a tendency for the small irregularities in the contours to be smoothed over and lost.

Berman had concentrated his attention on a small number of the brighter planetaries. In 1943, the present writer, then at the University of California, initiated a program to extend these studies to a number of additional objects. The plan was to measure the relative intensities of the brighter nebular lines and also the isophotic contours for some of the images of the larger planetaries. The plates also were obtained with the quartz slitless spectrograph on the Crossley Reflector. The first part of the program was carried out, but the second part was deferred until some machine such as the balanced beam isophotometer could be employed on the problem. Before these observations could be reduced, Wilson secured vastly superior plates with the coudé spectrograph at the 100-inch telescope.

3. The Mt. Wilson and Palomar Observations of the Planetaries

The technique used by Olin Wilson to secure slitless spectrograms with the coudé spectrograph is the following: He replaces the slit-head normally used for stellar work by a tube covered with a silvered, hinged mirror. The observer places the image of the planetary on the mirror and centers it as seen on a reticle in the guiding eyepiece. The hinged mirror is raised during the exposure. Hence, unlike with ordinary astronomical photography, the observer cannot guide while the light is falling on the plate. Securing good images by this method calls for considerable skill, but Wilson has obtained some excellent observations.

One further remark must be made. At the coudé focus of a large reflector the image slowly rotates with respect to the slit-head during the course of a long exposure. In order to prevent a blurring of the nebular image it is necessary to employ an optical device known as an "image rotator" which keeps the orientation of the nebular image fixed with respect to the slit during the course of a long exposure.

In 1949, tracings from Wilson's plates showed that considerable information could be obtained on the structure of the nebular. Isophotic contours of the images of [OIII], Hβ, and [NeIII] were obtained for NGC 7662 by the method of successive tracings. The reductions were so time-consuming and tedious that it was apparent that some automatic method of reduction would have to be found if any number of nebulae were to be observed.

The coudé slitless technique is limited to relatively small nebulae of high surface brightness. It cannot be employed to study objects of low surface brightness nor the faint outer extensions of large nebulae.

Fortunately, large, faint planetaries as well as the smaller, brighter ones can be studied effectively on direct photographs obtained with appropriate plate-filter combinations. The plate filter combinations employed by Minkowski to isolate the various monochromatic radiations are as follows:

Table 1.

Emulsion type	Filter type	Radiation isolated
103a-E	RG 2 OR 1	Hα + [NII]
103a-D	CG 3486	Visual continuum near λ6000 A
103a-J	GG 11	[OIII]
103a-O	No. 2A + No. 35	λ4686
103a-O	No. 3 + No. 34A	Hγ
103a-O	CG 5840	λ3727

The use of filters often does not suffice to separate lines that are close together. In particular the λ6548, 6584 [NII] and λ6563 Hα are not separable, and conclusions concerning the distribution of the hydrogen radiation must be based on other lines of the Balmer series. On the other hand, it is possible to photograph nebulae in their continuous radiation, a feat which would not be possible with the slitless spectrograph.

One further remark must be made concerning the direct photographs. There is no distortion of the picture due to differential internal motions in the nebula. On the other hand, a slitless spectrogram is distorted if different parts of the nebula have different velocities. NGC 2392 provides an example in point. This planetary appears to have a broken double-ring structure with numerous knots and condensations. Minkowski and Wilson compared a direct photograph and a slitless spectrogram to find that the knots on one side of the central star appeared to be moving towards the observer - on the other side away from him! Slitless images of expanding shells are distorted by an amount that depends on the rate of expansion.

Table 2 lists the planetary nebulae observed with the slitless spectrograph. The first column gives the ion whose image is traced,

Table 2

Nebulae Observed with the Coudé Slitless

Ion	λ	J320	NGC 1535		IC 351		J900	IC 418[1]		NGC 2165		NGC 2392	NGC 2440	NGC 4593	NGC 6210
		8500	5989	8397	8456	8396	8498	6003	8501	8458	8502	6073	5999	5663	5858
[OIII]	5007	x		x	x	x	x	x	x	x	x	x	x	x	
"	4959	x	x	x	x	x	x			x	x		x	x	x
Hβ	4861	x	x	x	x	x	x	x	x	x	x	x	x	x	x
[AIV]	4744												x		
"	4712												x		
HeII	4686			x	x	x	x			x	x	x	x		x
HeI	4471							x							x
[OIII]	4363	x	x	x	x	x	x			x	x		x		
Hγ	4340	x	x	x	x	x	x	x		x	x		x	x	x
Hδ	4101		x					x							x
[NeIII]	3969		x												
H	3889	x										x	x		
[NeIII]	3865	x	x	x	x	x	x			x	x	x	x	x	x
[OII]	3727							x							x
[NeV]	3444												x		
"	3425										x		x		

Ion	λ	NGC 6572[2]			NGC 6741	NGC 6818	NGC 6886	NGC 7009		NGC 7026	NGC 7027		NGC 7662
		5867	5859	8387	5864	8591	8459	5860	5868	8499	8388	8395	5861
[OIII]	5007	x	x	x		x	x	x		x	x	x	
"	4959	x	x	x		x	x	x	x	x	x	x	x
Hβ	4861	x	x	x	x	x	x	x	x	x	x	x	x
[AIV]	4744	x		x				x					
"	4712	x		x				x					
HeII	4686				x		x	x	x		x	x	x
HeI	4471	x	x	x				x	x				
[OIII]	4363	x	x	x	x		x	x	x		x	x	x
Hγ	4340	x	x	x	x		x	x	x			x	x
Hδ	4101								x				
H	3889					x		x	x				
[NeIII]	3865	x	x		x	x		x	x	x		x	x
[NeV]	3444							x					x
"	3425						x						x

(1) IC 418. λ6563 image also was measured on plate 8501.

(2) NGC 6572. The [SII] 4068, HeI 4026, and H 3797 images were measured on plate 5867.

the second the wave length, and the following columns the nebulae which have been studied. A cross is entered in the body of the table for each line that is traced on each plate. The plates of the eight-thousand series were obtained by the writer who was a guest investigator at the Mt. Wilson Observatory in 1952. All of the other slitless spectrograms were made by Olin C. Wilson.

Table 3 lists the planetary nebulae observed with the 200-inch Hale reflector by R. Minkowski. Successive columns give the designation of the object, the right ascension and declination for 1950, and a reference to the radiation in which the object is observed. Most of the nebulae have been observed either in Hα + [NII] or [OIII]. The Ring Nebula, however, was observed also in λ4686, Hγ, λ3727 [OII], and in the continuum, while NGC 7009 was observed in λ4686 He II, and λ3727 in addition to Hα + [NII] and [OIII].

A few objects, i.e., NGC 6210, 7009, 7026, and 7662, have been observed both with the slitless spectrograph and at the primary focus of the 200-inch. The direct exposures of NGC 6210 were taken for the outer regions of the nebula, while the direct photograph of NGC 7026 was so superior to the writer's slitless plate that no comparison is possible.

4. Reduction of the Observations

In order to reduce a monochromatic image of a nebula to a series of isophotic contours it is necessary to know the relation between the blackening of the photographic emulsion and the intensity of the light. That is, a photometric calibration is necessary.

Since the slit-head is removed for the coudé slitless spectrograms, the calibration ordinarily employed for the stellar spectrograms cannot be used and recourse must be had to auxiliary calibration apparatus. For this purpose, Wilson and the writer customarily employed a wedge slit calibration spectrograph.

In addition, calibration checks were made from time to time with the coudé step-slit device.

At the 200-inch telescope, Minkowski secured for certain of the brighter planetaries a series of graded exposures. Keeping the exposure time fixed, he took on each plate a series with apertures of 200", 165", 138", and 118". The tracings of successive images of the same nebula then may be used to establish the necessary calibration curves.

The isophotic contours may be determined in principle by a number of methods. One method, which involves television techniques, has been described by T. L. Page, who, however, never developed it for actual quantitative work.

Table 3

Planetary Nebulae Observed with the 200"

			Notes
NGC 40	$0^h10^m11^s$	+72°14' 0"	(2)
NGC 650-651	1 39 9	+51 20	(3)
NGC 1501	4 2 39	+60 47 33	(3)
NGC 1514	4 6 8	+30 39 6	(3)
NGC 3242	10 22 31	-18 23 13	(1) (2)
NGC 3587	11 11 56	+29 35 18	(3)
NGC 6210	16 42 24	+23 53 27	(1) (2)
NGC 6302	17 2 57	-39 9.6	(2)
NGC 6369	17 26 17	-23 43 18	(2)
MHα 362 (1)	17 2 53	-10 4.7	(2)
CD -29°13998	17 44 45	-29 57.9	(2)
NGC 6537	18 2 15	-19 51.3	(2)
NGC 6720	18 51 44	+32 51 51	(2) (3) (4)
NGC 7009	21 1 27	-11 33 54	(1) (2) (3) (4)
NGC 7026	21 4 39	+47 38 39	(1) (2)
NGC 7662	23 23 30	+42 15 42	(1) (3)

(1) Graded exposures were obtained to give a photometric calibration.

(2) Hα + [NII] images was traced.

(3) [OIII] image was traced.

(4) λ4686 HeII and λ3727 [OII] images were traced.

The present investigation is based on tracings made with the balanced-beam isophotometer. This instrument, originally devised by Hiltner and Williams primarily for the reduction of stellar spectra has been rebuilt and improved by Edwin Dennison and Albert Boggess working under the supervision of Prof. Mohler. The machine contains two similar optical paths, in one of which is placed the photograph to be analyzed and in the other of which is placed the standard wedge. The operator first ascertains the relation between the photometric calibration of his plate and the standard wedge. That is, he determines the wedge settings corresponding to steps of, say, 0.1 in log I over the intensity range covered by the plate. In order to trace the contours for a certain log I, the corresponding wedge position is chosen. The machine will then seek the contour of exactly the same density in the photograph to be analyzed, As a motor drives the carriage containing the photograph along, the corresponding isophotic contour is traced.

The earlier version of the machine employed photographic recording. Later, a grant was obtained from the Horace H. Rackham Graduate School of the University of Michigan to purchase a Brown recorder so that the operator may see the actual contours traced before his eyes.

The machine traces not only the contours of regular nebulae and galaxies, but also such complicated planetaries as NGC 2392 or NGC 1514 and intricate diffuse nebulae like Messier 8, the Trifid nebula, and 30 Doradus.

The machine is normally used with magnifications of 50 or 100. Since the scale of the 200-inch reflector (without the coma-corrector) at the primary focus is 11."12/mm, this means that with the larger magnification 1" corresponds to very nearly 9 mm.

The coudé spectrograph produces a distortion of the image in the sense that on plates taken with the 9-foot focal length collimator usually used, the scale along the dispersion is too small with respect to that at right angles thereto in the ratio 0.758 to 1.00. Since the machine may be employed with different magnifications on the tracing paper in the two coordinates, it is possible to eliminate this unequal magnification and reproduce the contours without distortion! This has been done on all the slitless spectrograms.

A detailed account of the performance of the isophotometer is being published by Dennison in a separate communication.

5. Interpretation of the Results

The isophotic contours give a fairly complete description of the relative intensity distribution throughout the nebular image. In order to express the isophotic contours, not in arbitrary intensity units, but in absolute intensity units, e.g., in ergs/cm^2/sec/unit solid angle, it is necessary to obtain an independent set of observations of a different type.

This absolute calibration comprised the goal of two entirely independent investigations undertaken by my colleague Dr. William Liller and by Liller and myself. With a suitable photoelectric photometer and appropriate filters, Liller compared the brightness of the nebula in the green nebular lines with comparison stars of the same spectral class as the sun. Since the relative brightnesses of the comparison star and the sun are known, the energy radiated by the nebula in the green lines can be found. Accurate measures of the transmission curves of the filter, the photometer sensitivity, etc., are all required.

In the technique employed by Liller and the writer, an objective prism in front of the correcting plate of the Curtis Schmidt telescope of the University of Michigan provided short spectra of the stars and nebulae. Then the nebular spectra could be traced directly with the photoelectric photometer at the telescope and compared with similar tracings of a comparison star whose absolute energy distribution was known. The integrated monochromatic surface brightnesses obtained by the two methods are in excellent agreement with one another. Hence an absolute calibration of the isophotic contours may be made.

Unfortunately, the relatively small light-gathering power of the 24-inch aperture of the Schmidt camera limited our observational program to the very brightest planetaries with the result that many of the objects for which isophotic contours have been drawn have not been observed photoelectrically. We hope to remedy this situation by obtaining photoelectric observations with telescopes of larger light-gathering power. Until this has been done no attempt will be made to put all the isophotes on an absolute intensity scale.

A brief discussion of the accuracy of the isophotic contours traced by the machine may be given here. Detailed tests were made for NGC 7662, the bright double-ring planetary in the constellation of Andromeda.

The images of the green nebular lines of [OIII], Hβ, λ4686 HeII, and λ3865 [NeIII] upon slitless spectrograms of NGC 7662 obtained by O. C. Wilson were reduced by the writer using the Berman method of successive traces. These same images were later traced on the machine and the two sets of isophotic contours compared. Excellent agreement was obtained in the general over-all features of the nebula and in all of the main details. The hand-reduced tracings, however, tended to smooth over the fine structure in the nebulae so that the machine was capable of giving much higher accuracy.

A comparison of the green nebular-line image in NGC 7662 as obtained on a plate secured by R. Minkowski with the image of the same line on the previously mentioned slitless spectrogram was also made. The slitless image is blurred by the internal motions in the line of sight within the nebula. The direct photograph is not so affected. Hence a comparison of the two tracings should indicate the extent to which slitless images may be falsified by the blurring.

Superposition of the two sets of isophotic contours showed that for NGC 7662 the blurring effects of the internal motions upon the contours is small. The reason may be as follows: In the central part of the nebula where the radial velocities are large, the gradient of surface brightness is relatively small. The contours tend to be more sensitive to local irregularities than to velocity effects.

A more serious difficulty with the isophotes lies in the circumstance that many of Minkowski's plates had no photometric calibration. Some were developed under the same conditions as plates for which a calibration is available. For these, a mean calibration curve appears to suffice. For other plates, it is possible only to give tracings corresponding to selected densities, which cannot be expressed precisely in terms of intensities.

The nebulae selected for study show a wide variety in surface brightness and structure. They include fairly smooth, uniform, relatively regular objects at one extreme and very irregular objects at the other. Minkowski and Wilson are discussing the detailed characteristics of the forms and internal motions of the planetaries on the basis of their observations in a separate publication. Our own measures amount to quantitative descriptions of the nebular images and detailed publication plans will depend on their wishes.

Most theoretical work was based on a model planetary which consisted of a thin homogeneous shell surrounding a hot star. This mathematically attractive model was thought to be a good approximation to at least some planetaries. Unfortunately, the approximation appears to be a poor one; even the most regular appearing objects cannot be represented as uniformly thick, homogeneous shells.

In the northern hemisphere, one of the objects best suited for observation is NGC 7662. Early photographs by J. E. Keeler and by H. D. Curtis showed it to consist of a bright inner ring and a much fainter outer ring. The larger-scale Mt. Wilson and Palomar observations show that the outer ring has an extremely mottled structure; the inner ring is irregularly shaped and broken. The 4686 radiation is confined to the inner ring which has a markedly different appearance than it has in the radiation of [OIII] or [NeIII]. The homogeneous shell model will not work even as a zeroth order approximation, but some progress may yet be made by combining the observations made with Wilson's multi-slit with the isophotic contours.

The Ring Nebula is a well-known object which cannot be represented by a homogeneous shell model, or apparently even by a model in which the density of the radiating matter depends on only two variables r and θ. The 3727 [OII] image is the largest and brightest on the usual photographic emulsions. The surface brightness is highest along the minor axis and lowest along the major axis, but the ring itself shows a very filamentary structure. This object shows the stratification effects more strikingly than do any of the others and has long constituted a favorite illustration of the tendency for the

ions of higher excitation to be found nearer the central star. The small λ4686 HeII image tends to occupy the hollow of the λ3727 [OII] ring, but it cannot be represented as any kind of a uniform structure. The observations of NGC 6720 were not calibrated so that precise quantitative conclusions concerning this object cannot be drawn.

NGC 1514 shows a disk or ring structure with some remarkable features. The disk may be regarded as a surface of uniform brightness with numerous holes here and there. NGC 1535, NGC 3242, and NGC 7009 (which was discussed in last year's report) show many of the same features as NGC 7662 and cannot be represented by the uniform shell model.

The complicated Ring Nebula NGC 2392 shows a remarkably intricate structure. There appears to be a bright but very irregular inner ring and an outer ring with numerous knots and filaments. The isophotic contours are extremely complicated; there being numerous valleys and mountains. Unlike NGC 7662 where the λ4686 HeII radiation is restricted to the inner ring, the outer knots and filaments show the radiation of HeII as well as λ3727 [OII]. Here the stratification effects are almost completely masked by the complications produced by the inhomogeneities. The previously mentioned radial velocity measures indicate that a shell structure will not explain these observations. One side of the nebula appears to be approaching the observer; the other side is receding.

Most of the planetary nebulas, when observed with sufficient magnification, show a pronounced filamentary structure. Such a fine-structure is scarcely surprising in view of the fact that the Reynolds number for these objects must be much larger than a thousand. What is surprising is the smoothness shown by a few objects, of which NGC 3587, the "Owl Nebula," is the best example. Visual inspection of the best photographs, as well as the tracings made with the isophotometer, show an extremely smooth structure devoid of any irregularities larger than 0."5 in diameter. Either the turbulent structure is much smaller than this or some agency acts to prevent the turbulence. A detailed discussion of this object is being published by Minkowski and the writer in the Astrophysical Journal.

The turbulent structure of gaseous nebulae is perhaps best investigated in the relatively nearby , large, diffuse nebulae such as Messier 8 or Messier 20. Here the scale of the fine structure appears to be much larger than in the planetaries. The roughly symmetrical structure of many of the planetaries indicates that turbulence of the classical aerodynamical type cannot be the dominating feature. Rather, there must occur orderly, or nearly orderly, motions that break down into whirls and eddies under certain circumstances. Not enough is at present understood about the dynamics of compressible fluids to permit detailed predictions to be made.

At the present time, one of our graduate students, Albert Boggess III, is developing methods for the empirical study of turbulence in diffuse nebulae. We hope that these methods will be applicable to the planetaries for which we have striven to obtain good quantitative data.

Acknowledgements

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The isophotometer tracings were all made by Mrs. Nancy Boggess whose careful and painstaking endeavors made this program a success. Substantial help in the improvement of the isophotometer was provided by Messrs. Boggess and Dennison under the supervision of Mr. Mohler.

Finally, it is a pleasure to acknowledge the grant made by the Horace H. Rackham School of Graduate Studies to purchase a Brown recorder for the isophotometer.

References

The classical investigations on the planetary nebulae are given in Publ. Lick Obs. 13 (1918).

A summarizing account of our present knowledge of the planetary nebulae is contained in Chapter 5 of the writer's "Astrophysics, Nuclear Transformations, Stellar Interiors, and Nebulae," Ronald Press Company, New York (1954). At the end of this chapter a critical bibliography of planetary nebulae is given.